

Resonant Excitation of Plasma Wakefields using Multiple Electron Bunches

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Abstract. We plan to resonantly excite plasma wakefields using a train of electron bunches separated by an integer number of plasma wavelengths. The multiple electron bunches are generated by a photocathode based RF gun by splitting the laser beam into temporally separated pulses. The amplitude of the wakefields generated by the sequence of bunches is expected to be higher than that generated if all charge had been in only one bunch, because this single bunch would be considerably longer than the individual sub-bunches due to space charge effects in our gun.

INTRODUCTION

High charge short electron bunches are needed to achieve high accelerating gradients in electron beam driven plasma wakefield accelerators. Electron bunches generated by photocathode based RF guns in general become longer as the bunch charge is increased. An attractive alternative to generating high charge single electron bunches is to generate a train of bunches separated by a plasma wavelength (1,2). In this way the plasma wakefield is resonantly excited by the bunch train and each bunch can be kept short because the total charge is distributed over many bunches.

GENERATION OF MULTIPLE BUNCHES

We can generate multiple electron bunches from our photocathode based RF gun simply by splitting the laser beam into a sequence of temporally separated pulses. The delay between the pulses needs to be equal to the plasma wavelength, which in our case is about 6 mm (assuming a plasma density of $3 \times 10^{13} \text{ cm}^{-3}$). This delay between the laser pulses will introduce an energy difference between the various electron bunches in the train, as they will be emitted from the photocathode at different phases of the RF power that is present in the gun. However, since our RF gun operates at 1.3

GHz, we can generate three or four electron bunches separated by the required 6 mm without introducing an excessive energy spread between the bunches; electron bunches separated by 20 ps would have a launching phase difference of 9.4° .

Figure 1 illustrates how we plan to split the laser beam into four pulses. The laser beam would be directed onto two beam-splitters at near-normal incidence. Each beam-splitter has the appropriate dielectric coating on each surface, generating two pulses that are delayed by twice the optical thickness of the substrate. Thus, to generate pulses spaced by 6 mm we need a substrate approximately 2 mm thick with an index of refraction of 1.5. The two beam-splitters need to be separated by 3 mm. Table 1 shows the values of reflectivity for each of the four surfaces if four pulses of equal intensity are desired. Other charge profiles of the bunch train can be easily achieved by adjusting the reflectivity of the four surfaces.

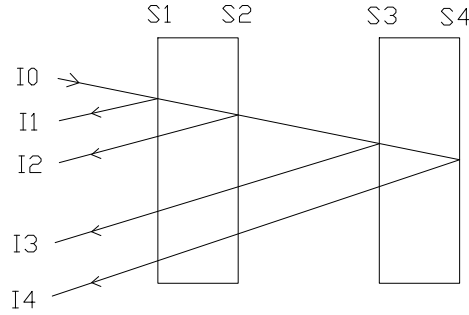


FIGURE 1. Laser beam splitting scheme. The incoming beam I0 reflects off of surfaces S1, S2, S3, S4, generating the beams I1 through I4.

TABLE 1. Beam Splitter Parameters

Surface	Reflectivity
S1	0.15
S2	0.21
S3	0.33
S4	0.74

THE AWA ELECTRON GUN PERFORMANCE

It is obviously easier to generate shorter electron bunches when the bunch charge is smaller. As we increase the bunch charge, space charge forces become more intense, in general making the bunch longer. We have measured the dependence of bunch length on charge for the AWA drive gun (3). Figure 2 shows the result of this measurement. Bunch length was measured with an aerogel Cerenkov radiator and a streak camera (Hamamatsu M1952/C1587). Bunch charge was measured with an integrating current transformer (Bergoz ICT-082-070-20:1). The plot shows the FWHM of the bunch length and also the 95% RMS values (i.e. the RMS calculated using only the section of the pulse profile with intensity within 95% of the peak value, with the purpose of discarding the effect of the small background noise at the wings of the distribution). The ratio between the 95% RMS and the FWHM values shows that the pulses are not gaussian. Each point on the graph corresponds to the average of three pulses. The large fluctuation in the FWHM of the pulses also shows that the detailed shape of the temporal profile varies considerably from pulse to pulse.

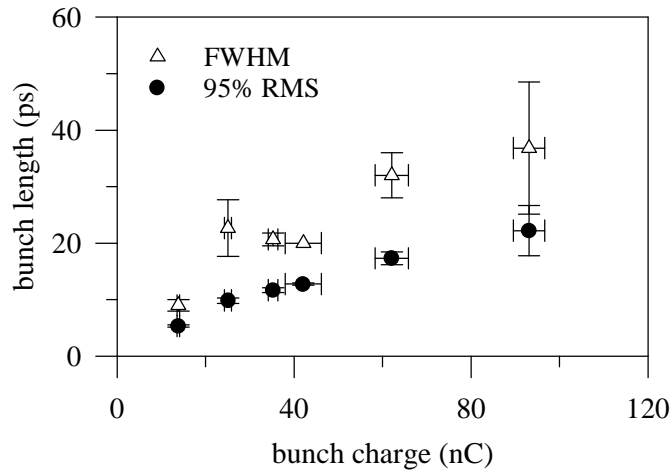


FIGURE 2. Measurements of electron bunch length as a function of bunch charge. The error bars indicate the standard deviation of the average of three pulses.

ESTIMATES OF WAKEFIELD AMPLITUDE

The amplitude of the plasma wakefield is approximately given by:

$$W_z(z) = \sum_m -\frac{E_0 F_m}{\sqrt{2\pi} \sigma_z} \int_{-\infty}^z \cos[k_p(z_0 - z)] \exp\left[-\frac{(z_0 - m \lambda_p)^2}{2 \sigma_z^2}\right] dz_0 \quad (1)$$

where σ_z is the RMS value of the bunch length, $k_p = 2\pi / \lambda_p$ is the plasma wavenumber, E_0 is the maximum amplitude of the field in V/m given by $E_0 = 192 n_0 Q$ with n_0 as the plasma density in cm^{-3} and Q as the bunch charge in nC; F_m is the coefficient associated with the bunch number m , such that the distribution of charge along the z axis is given by:

$$\rho(z) = \sum_m \frac{Q F_m}{\sqrt{2\pi} \sigma_z} \exp\left[-\frac{(z - m \lambda_p)^2}{2 \sigma_z^2}\right] \quad (2)$$

Figure 3 shows the wakefield amplitude as calculated from equation (1) for two different cases. The first plot (Fig. 3a) shows the wakefield that would be excited by a single bunch of 60 nC with $\sigma_z = 3.5$ mm. In this case the plasma density is equal to $6 \times 10^{12} \text{ cm}^{-3}$, and the wakefield amplitude has a peak of approximately 20 MV/m. The second plot shows that a considerably higher accelerating gradient of 100 MV/m can be achieved if the same amount of charge is distributed into four bunches of 15 nC, each one with $\sigma_z = 1.5$ mm. In this case, with this shorter bunch length, the optimum plasma density is about $3 \times 10^{13} \text{ cm}^{-3}$.

ACKNOWLEDGMENTS

We thank N. Barov for useful discussions. This work was supported by the Department of Energy, Division of High Energy Physics, under contract W-31-109-ENG-38.

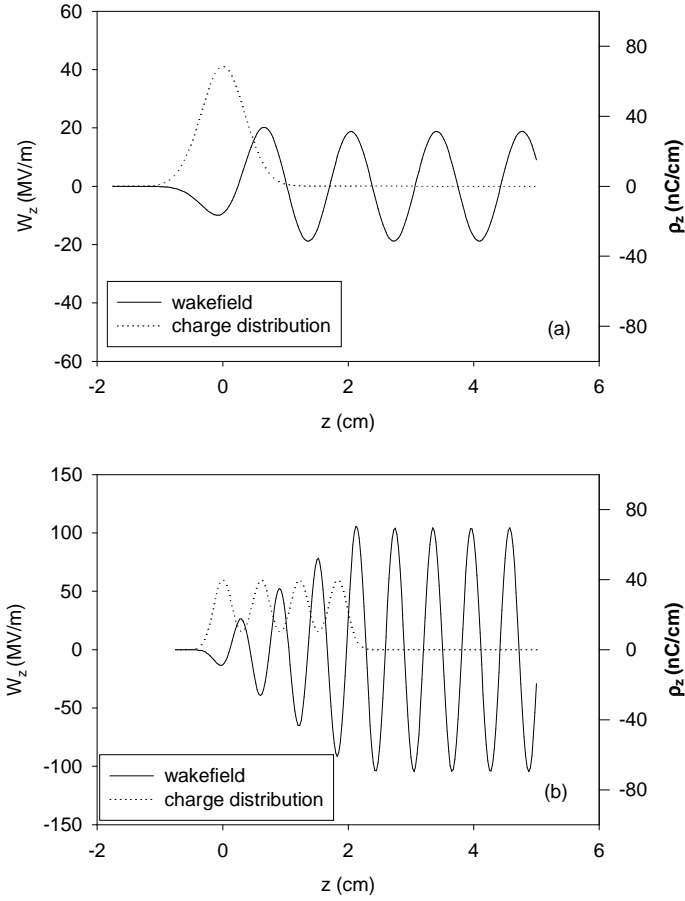


Figure 3. Wakefield amplitude and bunch charge distribution: (a) single 60 nC drive bunch with $\sigma_z = 3.5$ mm; plasma density is $6 \times 10^{12} \text{ cm}^{-3}$; (b) train of four 15 nC bunches with $\sigma_z = 1.5$ mm; plasma density is $3 \times 10^{13} \text{ cm}^{-3}$.

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